

THE LUNAR INTERIOR⁺

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Abstract

The compressional velocities are estimated for materials thought to be important in the lunar interior and compared with lunar seismic results. The lower lunar crust has velocities appropriate for basalts or anorthosites. Anorthosite is preferred if lunar basalts result from a small degree of partial melting. The high velocities associated with the uppermost mantle imply high densities and a change in composition to a lighter assemblage at depths of the order of 120 km. Calcium and aluminum are probably important components of the upper mantle and are deficient in the lower mantle. Much of the moon may have accreted from material similar in composition to eucrites. The important mineral of the upper mantle is garnet; possible accessory minerals are kyanite, spinel and rutile. If the seismic results stand up, the high velocity layer in the moon is more likely to be a high pressure form of anorthosite (garnet \pm kyanite \pm quartz) than eclogite, pyroxenite or dunite. The thickness of the layer is of the order of 50 km. Cosmic abundances can be maintained if the lower mantle is ferromagnesium silicate with minimal amounts of calcium and aluminum. Achondrites such as eucrites and howardites

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have more of the required characteristics of the lunar interior than carbonaceous chondrites. A density inversion in the moon is a strong possibility.

1. Introduction

High pressure phase equilibria studies on lunar basalts show that they would transform to high-density eclogites at relatively shallow depth in the moon and therefore the lunar interior cannot have the same composition as the surface material. These same studies have lead to various suggestions regarding the composition of the interior. Ringwood and Essene [1] favor pyroxenite (clinopyroxene + orthopyroxene + spinel or garnet); O'Hara et al. [2] suggest peridotite (olivine + pyroxene) and amphibole peridotite. The role of anorthosites has been stressed by Wood [3].

The Apollo lunar seismic experiment has provided additional information about the structure and composition of the lunar interior. The purpose of this note is to indicate the range of compressional velocity values for possible materials in the lunar crust and mantle.

Table 1 gives the densities and compressional velocities of various minerals and rocks that may be of importance in the lunar interior. There is a general tendency of velocity to increase with density for a given mean atomic weight. Iron content increases the density (and mean atomic weight) and decreases the velocity. Most of the values for oxides and minerals were obtained at room temperature and pressure on single crystals or sintered aggregates of near theoretical density. Natural rocks have intercrystalline cracks and pores and have very low velocities at atmospheric pressure; velocity increases rapidly with pressure as the cracks are closed. Experiment and theory show that it is very difficult to eliminate all the porosity in natural rocks but velocities measured at 10 kilobars are close to those

expected for a pore-free aggregate as can be seen from Table 1 by comparing dunite with olivine, of the same density, and pyroxenite with pyroxene. Rock values at 10 kb are taken as being appropriate for a theoretical assemblage of minerals at atmospheric pressure.

The effects of temperature and pressure on the velocities and densities are ignored in the following discussion. From the results of Anderson et al. [4] we can anticipate a velocity increase of 10^{-2} (km/sec)/kb and a decrease of 4×10^{-4} (km/sec)/°C. Thus, at 5 kilobars and 400°C, conditions near those expected at 100 km depth in the moon the velocities will be about 0.1 km/sec less than those estimated at zero-pressure and room temperature. Similarly, at corresponding conditions the density will be about 0.02 g/cm^3 less than estimated at standard conditions. The tendency for temperature to dominate over pressure in the moon was pointed out by Anderson and Kovach [5]. This leads to velocities and densities which decrease with depth over much of the lunar interior.

Oxides and high aluminum silicates such as garnet, jadeite and sillimanite have velocities in the range 8.53 to 10.85 km/sec. Iron-magnesium silicates are less than 8.57 km/sec and most ultrabasic rocks are less than 8.48 km/sec. Lunar rocks can be expected to have slightly higher velocities than corresponding terrestrial rocks because of the presumed absence of alteration.

2. Lunar Seismic Results

A preliminary structure of the lunar interior was presented by Toksoz et al. [6]. It is based on their analysis of seismic signals generated by impacts recorded on the Lunar Passive Seismic network. The velocity increases very rapidly with depth in the upper layer of the moon, in agreement with laboratory measurements on the returned lunar samples. Velocities in the

upper crust rise to about 6 km/sec and then increase abruptly at 25 km to 6.8 km/sec. The velocity is relatively constant, averaging about 6.87 km/sec down to a depth of 61 km where it increases rapidly again to a value near 9.2 km/sec at 74 km. The properties of the upper layer are presumably dominated by cracks, pores and intergranular effects and not much can be said about the composition. As Toksoz et al. [7] show, the velocities down to the first major discontinuity in the moon at about 25 km can be adequately explained by the effects of compression on the surface material.

Two candidates for the lower lunar crust, 25 to 60 km, are anorthosite and gabbro. Velocities measured on terrestrial anorthosites range from 7.02 to 7.21 km/sec at 10 kb which is in agreement with the mineralogy [albite, 6.5 km/sec, anorthite 7.2 km/sec and bronzite 7.85 km/sec]. Terrestrial gabbro's have compressional velocities of about 6.9 to 7.23 km/sec, measured at or extrapolated to 10 kilobars [7], again in agreement with the velocities of the component minerals. Thus the seismic data cannot distinguish between gabbro and anorthosite and both are acceptable components of the lower crust. Pyroxenites, dunites and eclogites can be ruled out at these depths. If all of the crust is composed of basalt it represents 16% by mass of the moon and at least this degree of partial melting would be required. Ringwood and Essene [1] suggest only 2-3% melting. Unless a greater degree of melting is allowed this leaves anorthosite as the major component of the crust and, we will show later, a possible major component of the upper mantle as well.

Toksoz et al. [7] obtained very high velocities, > 9 km/sec, at a depth of about 70 km. This is a very high velocity when compared with velocities at equivalent depths or pressures in the Earth's crust and mantle. For

example the velocity at the top of the earth's mantle is only 8.1 km/sec and important mantle rocks such as dunites and pyroxenites have velocities of 8.42 km/sec and 7.85 km/sec, respectively. Of the common rock-forming minerals only calcium-rich garnet (8.99 km/sec) and spinel (9.91 km/sec) have velocities as high as inferred at the top of the lunar mantle. Pyrope garnet is also predicted to have a high velocity.

Ringwood and Essene [1] and O'Hare et al. [2] showed that lunar basalts transform to eclogite at relatively low pressures. In fact, eclogite is the stable phase to the surface of the moon and the surface basalts must be metastable assemblages, prevented by kinetic factors from inverting to the denser mineralogy.

Ringwood and Essene [1] estimated the density of the eclogite as 3.74 g/cm^3 . This is a high density compared with terrestrial eclogites and we may expect that the seismic velocities may also be anomalous. As the above authors point out the high density of the eclogite phase, which presumably will be favored by kinetics at some depth in the moon precludes the entire moon from having the composition of the surface basalts. Similarly, anorthosite can be ruled out as the average composition of the moon. However, a thin layer of either of these assemblages in their high-pressure form is possible. Kanamori and Mizutani [8] measured velocities as high as 8.48 km/sec on eclogites having an initial density of 3.49 g/cm^3 . Approximately 5% of each rock was composed of hydrated minerals which serves to decrease the velocity by about 0.17 km/sec [Birch, 9]. Thus, the unaltered rocks would have a velocity of about 8.65 km/sec. Kumazawa et al. [10] measured velocities in the range of 8.46 to 8.62 km/sec for eclogites from Arizona and Utah having .

initial densities of 3.28 to 3.71 g/cm³. All of the above results refer to ten kilobars pressure - the pressure at which velocities in rocks containing cracks and pores approximate the velocities in aggregates of theoretical density at zero-pressure. Lunar eclogites can be expected to have slightly higher velocities because of the large (~ 10%) amount of rutile, velocity 9.26 km/sec. Because of the large effects of porosity and uncertain effects of alteration products it is difficult to estimate the in-situ velocities of rocks from measurements even at high pressure. An alternate procedure is to estimate the velocity from a mixture of single crystals which approximate the composition of the lunar eclogite.

A close match to the lunar surface composition and inferred eclogite density can be obtained by mixing grossularite garnet, almandine-pyroxene garnet, rutile and pyroxene.

Table 2 gives the compositions, densities and velocities of these four minerals. Although the minerals which have been measured do not have exactly the same compositions as their lunar counterparts, they can be mixed to give the appropriate density or the appropriate composition. A mixture of 19% pyroxene, 27% Al-Py garnet, 41% Gr garnet and 13% rutile gives close to the required density, 3.73 g/cm³ and gives a velocity of 8.66 km/sec. An alternative mixture which is closer to the average composition of the lunar surface material contains 31% pyroxene, 29% Al-Py garnet, 33% Gr garnet and 8% rutile; the density of this mixture however, is only 3.64 g/cm³; the velocity is 8.41 km/sec. Using Birch's relation to correct to the proper density we obtain $V_p = 8.74$ km/sec at a density of 3.74 g/cm³. These velocities are in good agreement with those actually measured on terrestrial eclogites, particularly when the difference in density and composition is taken into account.

A third way to estimate the velocity is from a velocity-density relationship proposed by Birch [12] and modified by Simmons [13] to take into account the effect of calcium. Using Simmons' relationship and allowing separately for the effect of TiO_2 we estimate a velocity of 8.64 km/sec from the density value and the CaO and TiO_2 content used by Ringwood and Essene [1]. Using Kanamori and Mizutani's relation between velocity and density we obtain an estimate of 9.2 ± 0.5 km/sec.

Mizutani has kindly provided the authors with the results of a detailed study of compressional velocities in lunar rocks. His plot of velocity vs. density extrapolates to 9.1 km/sec at a density of 3.74 g/cm^3 . The velocities and densities are uncorrected for length and volume changes due to compression. When corrected, using the data of Stephens and Lilley [11] the extrapolated velocity is 8.75 km/sec.

Our best estimate of the compressional velocity in lunar eclogites is 8.68 ± 0.04 km/sec. Higher velocities can be obtained by decreasing the iron content but the required decrease would move the eclogite stability field deep into the interior of the moon and the eclogite, of course, would no longer be isochemical with the basalt.

Pyroxenite is another candidate material for the lunar upper mantle. The inferred density of the pyroxenite that is stable in the outer 200 km or so of the moon is 3.27 g/cm^3 ; the composition given by Ringwood and Essene [1] corresponds to a mean atomic weight of 21.7. Using Birch's relation among velocity, density and mean atomic weight yields a compressional velocity of 7.8 km/sec. The Simmons' relationship, which allows explicitly for the CaO content, yields 7.74 km/sec. Using an approach similar to that used for

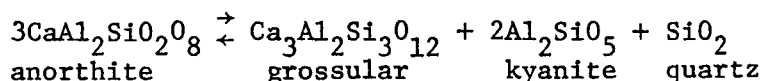
the eclogites, i.e. mixing minerals to obtain approximately the right density and composition, yields 7.5 km/sec. Birch measured the velocities on three pyroxenites and obtained an average value of 7.95 km/sec for material with an average zero-pressure density of 3.27 g/cm^3 . This is consistent with the measurements of Kumazawa [20] who obtained $V_p = 7.85 \text{ km/sec}$ for single crystal orthopyroxene of density 3.335 g/cm^3 . Clinopyroxenes have slightly lower velocities. At greater depth, depending on the temperature, spinel becomes a stable component of pyroxenite and the calculated density is 3.42 g/cm^3 and the velocity increase predicted by Birch's relation is about 0.5 km/sec, yielding a velocity of about 8.3 - 8.45 km/sec for spinel pyroxenite. The Simmons' relationship gives 8.15 km/sec. Garnet pyroxenites, stable at still higher pressures, with calculated densities of $3.46 - 3.52 \text{ g/cm}^3$ have predicted velocities of 8.3 - 8.6 km/sec. Therefore it is unlikely that pyroxenite in any of its phases is responsible for the 9.2 km/sec horizon.

O'Hara et al. [2] have suggested amphibole peridotite as a possible material for the moon's interior. This possibility is difficult to evaluate because of the scarcity of ultrasonic data on amphiboles and their highly variable nature. Hornblende, density 3.12 g/cm^3 has a velocity of 7.03 km/sec. Amphibolites which have been measured range in density from 3.03 to 3.26 g/cm^2 and range in velocity from 7.18 to 7.67 km/sec. Actinolite schist, density 3.19 g/cm^3 , has a velocity of 7.54 km/sec. These values are all slightly higher than measured for the lower crust and much lower than measured for the upper mantle.

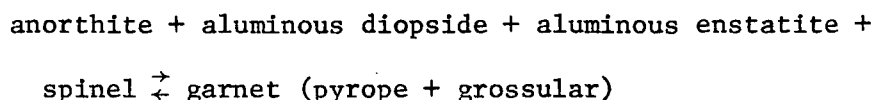
Anorthosite is probably an important component of the moon. As discussed above, anorthosites have relatively low velocities, 7.0 - 7.2 km/sec, and are

possible constituents of the lunar lower crust. Their velocities are too low for the upper mantle.

However, the reaction



is accessible at lunar pressures. The density of the right hand side is 3.54 g/cm^3 . Taking the velocity in sillimanite as an approximation to that of kyanite we obtain an average velocity of 8.94 km/sec for the right hand side of the above equation. If we take Birch's relation, $dV_p/d\rho = 3.31$ for isochemical compounds, we estimate a velocity of 11.14 km/sec for kyanite and an average velocity of 9.36 km/sec for grossular + kyanite + quartz. Five percent FeO will decrease this velocity by about 0.1 km/sec. This reaction occurs at lower temperatures than the gabbro-eclogite reaction and it is possible, with present estimates of the lunar temperature, that the 70 km discontinuity represents a phase change from low pressure to high pressure anorthosite. If the discontinuity is due to the gabbro-eclogite phase change it would represent the depth at which kinetics are favorable, not an equilibrium boundary. High velocities can also be obtained with the reaction



The above reaction results in a garnet having a composition of approximately 75% pyrope and 25% grossular. The velocity in pyrope is estimated to be 9.1 km/sec from the relation between V_p and weight percent FeO + MnO so that the garnet in the above reaction will have a velocity greater than 9 km/sec and will be only slightly less with the FeO content of lunar anorthosites. If

kinetics permit, this reaction may occur at 700°C and 5 kbar (Kushiro and Yoder, 1966) in the iron-free system which is close to the gabbro-eclogite transformation. This composition garnet would have a density of about 3.57 g/cm³. The high densities associated with both of the above assemblages preclude them from being the material of more than a relatively thin layer.

If the seismic velocities at the top of the lunar mantle are taken literally (there are many reasons to be cautious at this stage) anorthosite or anorthosite plus aluminous pyroxenes in a high pressure assemblage in the most plausible composition. Pyroxenites and eclogites have velocities which are too low. Eclogites can be ruled out if basalts represent only two or three percent of partial melting; under these conditions a 20 km thick layer of basaltic composition is all that the moon can yield. Pyroxenites are probably important below some 120 km; this is consistent with estimates of basalt origin depths.

2. Mass and Moment of Inertia

A layer of eclogite or of a dense anorthosite mineralogy can be accommodated by the requirements of the lunar mean density and moment of inertia. For example, if we postulate a near surface density of 3 g/cm³ and a lower crustal density of 3.36 g/cm³ which correspond, respectively, to uncompact and rock densities of basalt, and a lunar interior density of 3.37 g/cm³, corresponding to a dunite or pyroxenite, a 50 km thick layer of 3.7 g/cm³, corresponding approximately to eclogite, can be tolerated. This is Moon I in Table 3.

An alternate model with lower crustal densities of 3.1 g/cm³, corresponding to basalts and anorthosites, and an inner moon of density 3.43 g/cm³, appropriate for lunar pyroxenites (Ringwood and Essene, 1970) will accommodate

a 50 km thick layer of garnet + kyanite + quartz, the high P-T assemblage of anorthosite. The mean density, $\bar{\rho}$, and moment of inertia, $I = C/MR^2$, of these two models are given in Table 3.

The lunar basalts and anorthosites both contain much more Al_2O_3 and CaO than ordinary and carbonaceous chondrites. The amounts are comparable to eucrites and howardites. If the moon is to be chondritic in composition then the deep interior must be deficient in these oxides and this region must be mainly a ferromagnesium silicate such as dunite or pyroxenite. Mass and moment of inertia considerations restrict the density of the interior to about $3.40 \pm .03 \text{ g/cm}^3$ if the above estimates of the density of the overlying layers are correct. An olivine or pyroxene mineralogy also has the required property of not undergoing phase changes at lunar pressures. A velocity reversal must accompany this density reversal; velocities of 7.8 to 8.0 km/sec can be expected for the deep interior. A velocity reversal at depth will cause defocusing of seismic energy and will create a shadow zone phenomenon. Some difficulty might be expected in recording distant seismic signals.

4. Discussion

If the high velocities below 70 km reported by Toksoz et al. remain valid there must be a layer in the moon whose properties are dominated by some of the following minerals: garnets, spinel, kyanite, rutile. All of the above are possible components for a deep lunar mineralogy. Less plausible mineralogies with high compressional velocities are corundum, periclase and jadeite. In any case, calcium and aluminum are important constituents of the lunar upper mantle, and the high velocity-high density mineralogy cannot persist to great depth because of constraints imposed by the mean density and

moment of inertia of the moon. The low density of the moon and the importance of calcium and aluminum in the lunar crust and upper mantle suggest that eucrites or howardites may have been more important than chondrites in the accretion of the moon.

Achondrites such as eucrites and howardites have many features in common with the implied characteristics of the lunar interior. First of all they are high in calcium and aluminum. They are similar in composition to the surface rocks [14] as anticipated by Duke and Silver [15]. They are much less dense than most stoney meteorites. Ordinary chondrites are much too dense to be representative of average lunar composition and carbonaceous chondrites are too volatile rich if surface conditions on the moon are typical of conditions in the interior. Some of the eucrites have radioactivities which agree with the average radioactivity of the moon [Hanks and Anderson, in preparation]. A large part of the moon may be eucritic in composition, especially if the estimates [1] of the composition of the parent material of the lunar basalts are correct.

Having demonstrated the apparent importance of calcium and aluminum in the lunar lower crust and upper mantle it is of interest to calculate the average composition of the moon. Assume that the moon is 3% basalt, 20% anorthosite (lower crust and upper mantle) and 77% pyroxenite. The average composition is shown in column (1) of Table 4. This procedure probably yields close to an upper bound for the CaO and Al_2O_3 contents of the moon. However, even if the lower mantle of the moon is barren of CaO and Al_2O_3 we still obtain values greater than carbonaceous chondrites. If the lower mantle is richer in FeO and depleted in CaO and Al_2O_3 relative to the

Ringwood-Essene pyroxenite, or if there is much more basalt than assumed above, all of the oxides can be brought into the range between eucrites and chondrites. Both alternatives imply a severally differentiated moon.

The abundance of CaO and Al_2O_3 in the lunar interior emphasizes the importance of high temperature accretion. Calcium and aluminum rich compounds are among the first to condense from a cooling nebulae of cosmic composition. For example, $\text{Ca}_2\text{Al}_2\text{SiO}_7$, $\text{Ca}_3\text{MgSiO}_8$, $\text{Ca}_2\text{MgSi}_2\text{O}_7$, CaTiO_3 , MgAl_2O_4 , Al_2SiO_5 , $\text{CaAl}_2\text{Si}_2\text{O}_8$ and Al_2O_3 all condense before Fe or such silicates as MgSiO_3 and Mg_2SiO_4 [24,25]. Immediately following Fe and preceding MgSiO_3 and Mg_2SiO_4 are Ca_2SiO_4 , CaSiO_3 , $\text{CaMgSi}_2\text{O}_6$ and KAlSi_3O_8 . All of the important calcium rich condensates appear before Fe and $\text{NaAlSi}_3\text{O}_8$ is the only important aluminum rich compound that condenses after MgSiO_3 and Mg_2SiO_4 . Studies of trace elements also indicate enrichment of the high temperature condensates and depletion of the low temperature condensates at least on the lunar surface. The lack of iron in the moon may indicate that lunar accretion was nearly complete before iron began to condense in quantity or that iron, because of its high density, sank rapidly to the median plane of the nebulae and was swept up preferentially by the earth, both because of its larger mass and its low inclination orbit. The earth would accrete faster, become the larger body and be enriched in the later condensates, i.e. the volatiles, compared to the moon, simply because it is accreting in the denser part of the nebulae, i.e. the median plane. The moon (and eucrites and howardites) may represent the average composition of the high temperature condensates and the early material to accrete into planets. Carbonaceous chondrites, particularly type I, can be considered to be formed at the latter stages of the condensation

process and, presumably, representative of the material involved in the latter stages of accretion. Larger planets, such as the earth, cannot be expected to be similar in composition to any one meteorite class but can be considered to be made up of material that has condensed over a wide range of temperatures.

5. Summary

The seismic compressional velocities in the lower crust of the moon, 25-70 km, can be closely matched by either gabbro or anorthosite. Amphiboles have velocities which are slightly too high. Gabbro can be ruled out if lunar basalts form by a small degree of partial melting of the interior and if basalts are a major component of the upper crust.

The following estimates have been made of the compressional velocities in lunar rocks:

eclogite 8.68 ± 0.04 km/sec, H.P. anorthosite 8.8-9.3 km/sec
anorthosite pyroxenite 9 km/sec,
felspathic pyroxenite 7.7 - 7.8 km/sec,
pyroxenite 8.2 - 8.5 km/sec and
garnet pyroxenite 8.3 - 8.6 km/sec.

The seismic velocity at 70 km is greater than expected for eclogites, pyroxenites, amphiboles or anorthosites with their normal low-pressure mineral assemblage. Eclogites are the closest match, particularly if they contain less FeO than the surface material. The quantity of material of basaltic composition, however, is again a problem if the upper crust is basaltic and if the limited partial melt hypothesis is valid. The high pressure form of anorthosite (pyrope-grossular garnet \pm kyanite \pm quartz)

gives the appropriate velocity at 70 km. A 50 km thick layer of eclogite or H.P. anorthosite can be accommodated by the lunar mass and moment of inertia. The lower mantle of the moon is less dense, and has lower seismic velocities, than the upper mantle and is probably deficient in Al and Ca. Much of the moon may have accreted from material similar in composition to eucrites.

Both the mineralogy and the dominance of temperature over pressure indicate that the moon is unstably stratified.

The above considerations and alternatives, and the high surface concentration of uranium, lead to the conclusion that the moon is an extremely well differentiated body. Thermal history calculations also suggest that the moon was close to or in excess of melting [solidus] temperatures throughout most of its volume early in its history [Anderson and Phinney, 16]. An alternative is that the stratification of the moon is a relic of an inhomogeneous accretion. This will be discussed elsewhere.

Acknowledgments

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Table 1

Velocities and densities in oxides, silicates and rocks

<u>Oxides</u>		ρ (g/cm ³)	V_P (km/sec)
MgO	periclase	3.58	9.69
Al ₂ O ₃	corundum	3.97	10.85
MgAl ₂ O ₄	spinel	3.62	9.91
CaO	lime	3.29	7.95
TiO ₂	rutile	4.26	9.26
<u>Silicates</u>			
SiO ₂	quartz	2.65	6.05
Mg ₂ SiO ₄	olivine	3.22	8.57
(Mg,Fe) ₂ SiO ₄	olivine	3.31	8.41
(Mg,Fe)SiO ₃	pyroxene	3.34	7.85
NaAlSi ₂ O ₆	jadeite	3.33	8.86**
Al ₂ SiO ₅	sillimanite	3.19	9.73
(Mg,Fe) ₃ Al ₂ Si ₃ O ₁₂	garnet (Al-py)	4.16	8.53
Ca ₃ Al ₂ Si ₃ O ₁₂	garnet (gr)	3.56	8.99*
<u>Rocks</u> *			
Dunite		3.31	8.42*
Dunite		3.74	7.36
Pyroxenite		3.25	8.01*
Pyroxenite		3.28	7.83*
Pyroxenite		3.29	8.02*
Eclogite		3.44	8.01*
Eclogite		3.49	8.48

Table 1 (continued)

<u>Rocks*</u>	ρ (g/cm ³)	V_p (km/sec)
Eclogite	3.51	8.47
Gabbro	2.93	7.21
Gabbro	3.05	7.23
Anorthosite	2.77	7.02
Anorthosite	2.77	7.10
Anorthosite	2.81	7.21

* 10 kb.

**4.5 kb

Compiled from Anderson et al. [4], Manghnani [17], Birch [18], Simmons [13],
 Hughes and Nishitake [19], Kanamori and Mizutani [8]
 Kumazawa et al. [10] and Kumazawa [20]

Table 2

Lunar Density Models

Radius (km)	Moon	
	I	II
	ρ (g/cm ³)	ρ
1738	3.00	3.00
1728	3.00	3.10
1702	3.36	3.10
1642	3.70	3.54
1592	3.37	3.43
$\bar{\rho}$	3.36	3.38
I	0.401	0.399

Table 3

Composition of minerals used to synthesize
properties of lunar eclogite and composition of lunar materials

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
SiO ₂	56.9	37.6	39.1		38.8	41.6	42.1	53.1	37.0	41.4
MgO	31.8	5.1	0.2		12.0	8.0	7.4	22.5	7.5	11.4
FeO	10.2	33.5	5.4		13.0	17.2	15.4	13.5	13.2	14.7
Al ₂ O ₃	9.2	21.4	19.6		15.5	10.6	13.6	5.0	13.9	12.8
CaO	0.1	1.1	34.9		12.3	10.6	11.3	4.0	14.6	11.9
NiO	0.1									
Na ₂ O					1.0	0.5	0.5	0.1		
TiO ₂			0.2	100.0	5.0	10.3	7.7	1.0	13.0	8.0
MnO			0.4			0.3		0.4		
ρ (g/cm ³)	3.34	4.16	3.54	4.26					3.73	3.64
V _p (km/sec)	7.85	8.53	8.99	9.26					8.66	8.41
Mix 1	0.19	0.27	0.41	0.13						
Mix 2	0.31	0.29	0.33	0.08						

(1) orthopyroxene [20]

(2) almandite-pyrope garnet [22]

(3) grossularite garnet [18]

(4) rutile [17]

(5) titaniferrous garnet, Apollo 11 synthetic eclogite, 27 kb, 1360°C [1]

(6) Apollo 11 basalt [1]

Table 3 (continued)

- (7) Apollo 11 fines [22]
- (8) Model lunar pyroxenite [1]
- (9) Mix 1; synthetic lunar eclogite based on density
- (10) Mix 2; synthetic lunar eclogite based on composition

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Table 4

Composition of the Moon and Meteorites

	(1)	(2)	(3)	(4)
SiO ₂	49.8	48.2	49.2	33.3
MgO	19.1	8.4	11.8	23.5
FeO	12.2	15.7	15.6	35.5
Al ₂ O ₃	9.6	15.6	10.0	2.4
CaO	11.1	10.4	7.7	2.3
TiO ₂	1.1	0.3	0.1	

- (1) Average lunar composition 3% basalt, 20% anorthosite, 77% pyroxenite
- (2) Eucrite, Moore Co. [15]
- (3) Howardites [14]
- (4) Carbonaceous chondrite, C,S and H₂O free [23]